Lateral Variations of aerosols and meteorological properties in off-shore winds

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ABSTRACT

Aerosol particle size distributions and meteorological parameters were measured during the MAPTIP experiment in the fall of 1993 in the vicinity of MeetPost Noordwijk (MPN), a platform at 9 km from the Dutch coast. One data set was collected at MPN, the other on board of a ship that sailed down and cross wind trajectories from MPN to a distance of 200 km. Both the aerosol concentration and extinction respond to variations in the meteorological conditions. For down wind trajectories, the responses at ship and platform are observed with a delay in accordance with the time it takes for an air mass to travel from one to the other. For cross wind trajectories, the responses are observed simultaneously at ship and platform. The comparison of ship and platform also shows that the meteorological conditions change as a function of fetch in off-shore winds. This fetch effect does not show up clearly in the aerosol concentrations, which suggests that in off-shore winds the influence of the land (natural, industrial and urban aerosol) extends up to more than 200 km from the coast.

Keywords: marine aerosols, aerosol dynamics, lateral variability, coastal influences, extinction, MAPTIP

1. INTRODUCTION

When an air mass is advected from land to sea, an abrupt change in the surface conditions is experienced at the land-sea transition. The surface roughness, the surface temperature and in particular the aerosol dynamics may change drastically. The aerosol particles generated over land (natural, industrial and urban) occur mainly in the small particle fraction (1 μm and less), whereas the aerosol particles generated in the surf zone (wave breaking) and at open sea are of larger size (typically 1-10 μm). Since the sea acts as a sink for aerosol of all sizes, the particle size distribution will change as the air mass is advected over the sea. At the same time, also the meteorological parameters, which to a large extent determine the aerosol dynamics, change with fetch. This dynamical behaviour involves the formation and evolution of an internal boundary layer. In these non-equilibrium conditions the current formulations for the vertical structure of the marine atmospheric surface layer do not apply until a new steady-state situation has been established.

The air mass over a coastal sea in off-shore winds contains a mixture of land-originated and marine aerosol. This mixed origing was demonstrated for the North Sea,[1] as well as for other regions such as the Mediterranean.[2,3] For the MPN platform (MeetPost Noordwijk) in the North Sea, at 9 km from the Dutch coast (see also Figure 1), it was shown[1] that the ratio of small (0.5 μm) and large (5.0 μm) is a function of fetch, with a larger amount of small particles for shorter fetches. For the shorter fetches, the concentration of small particles (mainly generated over land) decreases with wind speed, in line with an increased diffusion rate[4] in the absence of sources. On the other hand, the concentration of large particles (mainly generated over sea) increases with wind speed, which reflects the increased production rate.[5] The predominant land and marine origin of the small and large aerosol size fractions was later established by e.g., Van Eijk et.al.,[6] with Total-Reflection X-Ray Fluorescence (TXRF) elemental analysis of cascade impactor samples.

The analysis of Van Eijk and De Leeuw[1] also revealed that the time evolution of the aerosol size distribution is strongly influenced by frontal passages, thus showing another aspect of the dependence of the aerosol concentration on the meteorological scenario. The changes in the particle size distribution associated with frontal passages can be attributed to both changes in meteorological parameters (e.g., the relative humidity) and changes in origin of the air mass (e.g., continental before and maritime after the frontal passage). Typically, the aerosol distribution responds within a short time (less than 1-2 hours) to the new environmental conditions.

The changes in particle size distribution are reflected in the aerosol extinction (related to the size distribution by Mie theory). Thus, the extinction also depends strongly on fetch and meteorological scenario, and widely accepted models which perform well in open-ocean conditions cannot reliably predict the extinction in coastal regions with influence from the nearby land.[3,7]

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During the MAPTIP (Marine Aerosol Properties and Thermal Imager Performance) experiments attempts were made to address the lateral variability of meteorological parameters and the aerosol concentration in the coastal zone. MAPTIP was organized in the region around the MPN platform from 11 October - 5 November, 1993.[8] A research aircraft from NRaD, San Diego CA, was used to map the aerosol and meteorological parameters in the vicinity (up to 10 nMi) of MPN during 2-hour star-pattern flights (2 flights per day). Strong gradients were observed over these distances and plumes were clearly identified.[9]

In addition to the aircraft measurements, the oceanic research vessel H.Nl.Ms. Tydeman of the Netherlands Royal Navy measured aerosol concentrations and meteorological parameters along trajectories (both down wind and across wind) of up to about 200 km, starting from the MPN platform. At the same time, aerosol and meteorological parameters were recorded at MPN for reference. In this contribution we present the results from the ship/platform comparisons. A case study shows that the aerosol concentration responds to changes in meteorological parameters, and that these occur at ship and platform occur with a delay in accordance with air mass travel time. The lateral variability of meteorological parameters and aerosol concentration is also discussed.

2. EXPERIMENTAL

Aerosol size distributions at MPN were recorded with a Particle Measuring System CSAS 200 P (0.2 - 20 μm diameter range). The probe was mounted on a small platform extending North, at about 15 m above mean sea level. This position was chosen to measure in the NE winds, which prevailed troughout the experiment, unperturbed by the MPN platform. The particle size distributions were averaged over 10 minutes periods and stored with meteorological parameters from the MAPTIP consensus data set.

Aerosol size distributions at H.Nl.Ms. Tydeman were recorded with two Particle Measuring Systems, an ASAS 300 A (0.16 - 3 μm) and a CSAS 100 HV (0.5 - 32 μm). The instruments were mounted in a box on the roof of the bridge at about 15 m above mean sea level and the aspiration tubes were manually pointed into the wind. As on the MPN platform, the particle size distributions were averaged over 10 minutes periods and stored with meteorological parameters obtained from the H.Nl.Ms. Tydeman meteorological instruments.

Aerosol and meteorological data were collected continuously, 24 hours per day. Downtimes occurred because of rain, probe service and/or (temporarily) sensor failure. The MPN aerosol data of the first week of the experiment could not be used in the comparison, because the probe was then dedicated to vertical profiling. Small numbers of data records were removed from the H.Nl.Ms. Tydeman data set because they were polluted by the diesel exhaust from the stack. In the last week of the experiment, the ASAS-300 A probe was reliable operated only during day time, because frequent cleaning was required. All particle spectra that were incomplete were excluded from further analysis.

The remaining data set consists of approximately 1250 files of 10 minutes averages. Particle size distributions are stored in the data files as dN/dD values for each probe channel. The data files also contain the coefficients of two polynomials of orders 1 (Junge) and 5, which are fitted to the dN/dD values in (log dN/dD) versus (log D) space.

3. COMPARISON PLATFORM - SHIP

Since the aim of the present study is to compare the meteorological and aerosol data at H.Nl.Ms. Tydeman with those at the MPN platform, our first effort was to determine systematic differences between the various sensors at H.Nl.Ms. Tydeman and MPN. To this end, we selected the three periods during which H.Nl.Ms. Tydeman was anchored near (typically 1 km) the MPN platform and the two platforms must have been in the same air mass. A total of 248 data files was available for this comparison.

For the standard meteorological parameters (air and sea temperature, relative humidity, wind speed and wind direction) XY-scatter plots were made of the values measured at H.Nl.Ms. Tydeman and at MPN. Systematic differences were determined by linear regression. Most regression lines were close to the X=Y line, which means that the sensors at H.Nl.Ms. Tydeman and MPN platform did not differ significantly. The wind speed data was better described by a quadratic fit, i.e., the systematic differences became larger with higher wind speed. In high wind conditions the sensor at H.Nl.Ms. Tydeman measured higher values than the one at MPN. The scatter plots also allowed to estimate a significant difference between sensors at ship and platform, i.e., the minimum difference which cannot be regarded as scatter in the data. The significant differences are presented in table 1.

parameter	sign. difference
air temperature	± 0.20 °C
sea temperature	± 0.15 °C
relative humidity	± 3.50 %
wind direction	± 30 °N
wind speed	± 1 m/s at 5 m/s ± 4 m/s at 10 m/s

Table 1: Significant differences meteorological data

parameter	sign. difference
Junge exponent	± 0.50
C(0.5 μm)	± 0.30 (*)
C(0.5 μm) at 80% RH	± 0.30 (*)
C(5.0 μm)	± 0.25 (*)
C(5.0 μm) at 80% RH	± 0.40 (*)
	(*): in log (dN/dD)

Table 2: Significant differences aerosol data

A more elaborate procedure was necessary for the aerosol data, because the center diameters of the channels of the probes at the ship and the platform were not identical and the dN/dD data could not be directly compared. To determine the systematic difference between the aerosol size distributions measured by the probes at the ship and the platform, we used a method which is based on the assumption that all probes are of equal quality. Thus, during the anchor periods the actual aerosol distribution is best represented by a polynomial fit to all dN/dD data of the individual probes.

The first step of the procedure is to select two data files that were measured simultaneously at ship and platform, to merge the dN/dD data from all probes into a single distribution, and to fit a 5th order polynomial to this distribution. Subsequently, for each center diameter D_i of probe i, the differences $\delta(D_i)$ between the measured dN/dD value and the one calculated from the polynomial are stored. This process is repeated for all data files of the anchor periods. All the individual differences are then averaged to yield the mean differences $\Delta(D_i)$ for each channel of each probe. Each value $\Delta(D_i)$ represents the systematic difference between the measured dN/dD value and the one that is calculated from a best fit to all available data.

In the second step, the $\Delta(D_i)$ values are used to correct the measured aerosol distributions for systematic probe differences. In each file (anchor periods and tracks) of each data set (ship and platform) the correction factors $\Delta(D_i)$ are added to the corresponding dN/dD values. A new 5th order polynomial and Junge distribution are fitted to the corrected data, and data and fits are stored in a new data file. In this way, each distribution of a single probe is corrected to the common distribution of all probes.

Were the correction ideal, any remaining differences in aerosol concentration between ship and platform could be attributed to differences in meteorological scenario and/or geographical location. Scatter plots of aerosol concentrations measured during the anchor periods at the ship and platform were made to infer the significant difference (cf. the discussion above for the meteorological parameters), or in other words, the reliability of our correction method. Table 2 shows the results for two diameters, i.e., 0.5 and 5.0 μm, which are representative for aerosol of land and marine origin, respectively. In addition, the significant difference for the Junge exponent is presented, which gives a more general indication of the reliability of the correction method.

After the correction for systematic differences, the aerosol distributions were normalised to a relative humidity of 80% by a procedure given by Fitzgerald.[10] This was done to remove humidity induced changes in particle size due to evaporation or condensation. Table 2 shows the significant differences calculated for the normalised data set, which are somewhat larger than for non-normalised set. The reduced reliability is probably caused by the fluctuations between the humidity sensors at ship and platform, which become particularly important in high humidity conditions (RH > 95%).

4. LATERAL VARIATIONS

During the MAPTIP experiment, H.Nl.Ms. Tydeman made a total of eight treks from MPN over the North Sea to distances of about 125-200 km from MPN and with time spans of about 12-30 hours between departure from and arrival at MPN. A map with the treks is shown in Figure 1. A comparison of aerosol data between ship and platform was meaningful for treks 3, 4 and 5 (cf. section experimental).

Trek 3 of H.Nl.Ms. Tydeman was in South-Western direction, to a position near the UK coast at a distance of about 100 nMi from MPN (cf. Figure 1). At the end of the outward leg, the ship anchored 13 hours before starting the return trip to MPN. The trajectory was exactly down wind from MPN for the most of the case (course 245°, wind direction 60°). Towards the end of the trek, the wind direction changed to 30°. The change in wind direction is associated with a displacement of a strong high pressure system from Ireland to Scotland. The system at that time dominated the whole North Sea area and the change in wind direction lead to a longer fetch for the air mass arriving at MPN. This was reflected in an increase in humidity and air temperature (warming of cold air over warm sea), and a decrease in the concentration of small (0.5 μm) land-originated aerosol.

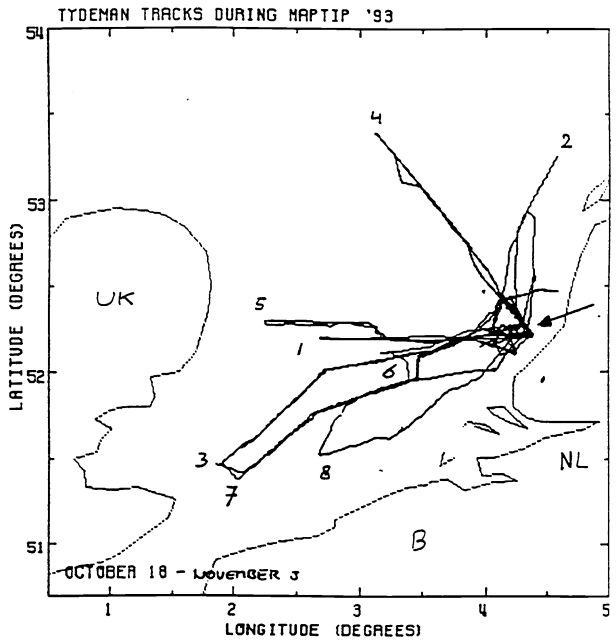

Figure 1: Composite sailing schedule of H.Nl.Ms. Tydeman recorded by the Hyperfix system. The arrow indicates the location of MPN.

Since H.Nl.Ms. Tydeman sailed down wind, it was expected that weather changes at the platform preceeded the changes at the ship. With a maximum separation of 100 nMi and a wind speed averaging to about 12 m/s, the maximum delay between the weather changes at the two stations was about 4.5 hours. The expected delays showed up most clearly in the evolution of the wind speed. Figure 2 shows the wind speed measured at MPN (✳) and H.Nl.Ms. Tydeman (o) during the case. The time scale is in Julian date, where 297.5 corresponds to October 24, 12.00 am. The "S" denotes the time at which the ship started her sail from MPN, the two "E" flag arrival at and departure from the anchor position, and the "R" marks the time that H.Nl.Ms. Tydeman was back at MPN. Since we have noted a systematic difference between the wind speed measured at both stations (cf. previous section), we will only discuss the relative changes at the two stations. Starting at 297.5, the wind speed at MPN decreased from 10 m/s (marked 1) to 5 m/s (marked 2), increased to 9 m/s for a short while (marked 3), and decreased again (marked 4). The same behaviour is visible in the ship's data (marks A-D),

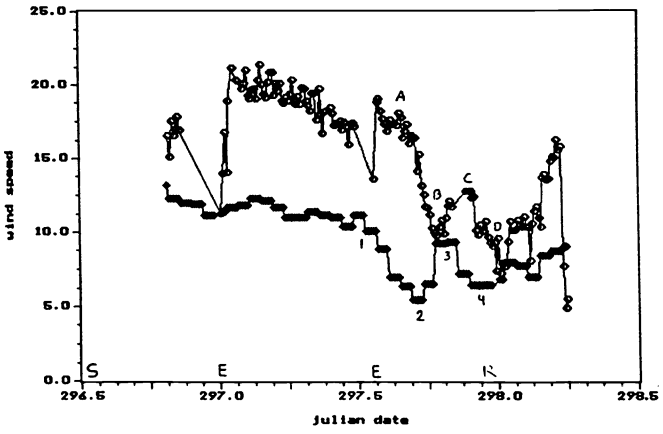

Figure 2: Time series of wind speed at MPN (✦) and ship (o) during trek 3. "S", "E" and "R" denote start, anchor period and end of trek, respectively.

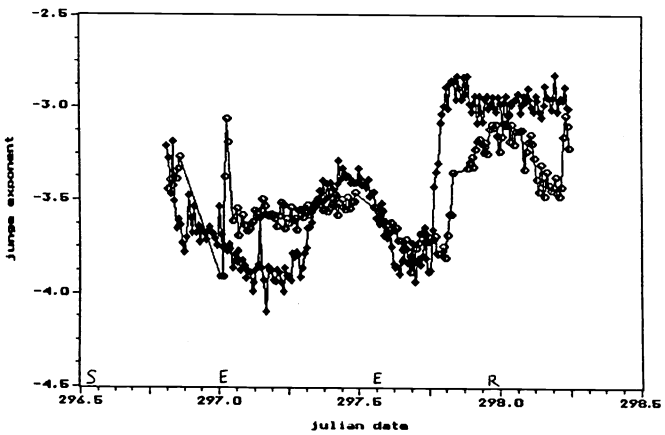

Figure 3: Time series of Junge exponent at MPN (✦) and ship (o) during trek 3."S", "E" and "R" denote start, anchor period and end of trek, respectively.

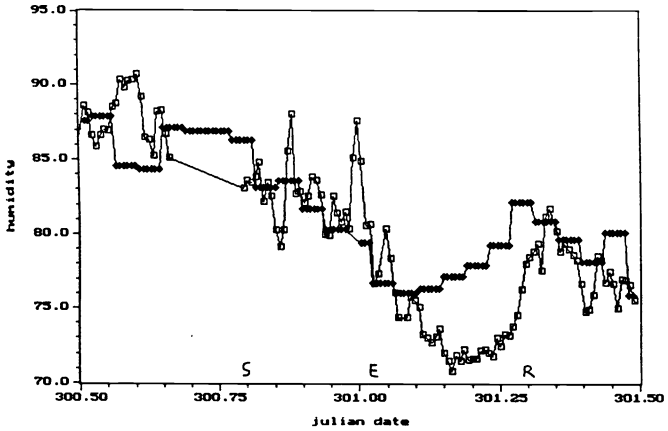

Figure 4: Time series of relative humidity at MPN (✦) and ship (□) during trek 5."S", "E" and "R" denote start, turning point and end of trek, respectively.

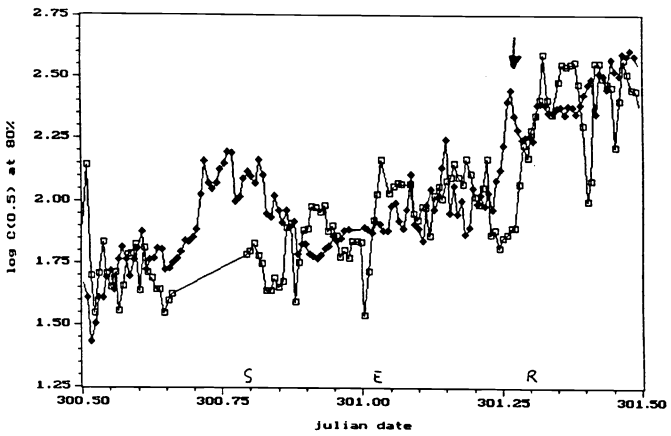

Figure 5: Time series of (log dN/dD) of 0.5 μm particles, normalized to a relative humidity of 80%, at MPN (✦) and ship (□) during trek 5.

but with a delay ranging from about 2.5 hours (mark A) to 30 minutes (mark D). The decrease in delay times corroborates with the ship sailing back to MPN.

The concentration of small (0.5 μm) particles measured at the two stations did not vary much during the event (except for the decrease at MPN explained above as a fetch effect), and possible delays in changes at platform and ship remained hidden in the noise. In contrast, the concentrations of larger particles showed significant variations which were reflected in the spectral slope of the particle size distributions, represented here as the Junge exponent (Figure 3). When the number of large particles increases, for constant concentrations of smaller ones, the Junge exponent increases as well (becomes less negative). Because the Junge exponent is determined as a least squares fit to the particle size distribution, the noise in this parameter is smaller than the fluctuations in particle concentrations. Figure 3 shows that in the evening of October 25 (Julian date 298.85) the Junge exponent increased considerably. The increase was observed about 1.5 hours earlier at MPN than at the ship, in accordance with the delay expected on the basis of wind speed and distance.

The aerosol extinction at the two stations was calculated from the particle size distribution using a Mie code. The time eseries of the 10.6 μm aerosol extinction at 10.6 trails that of the Junge exponent. This strongly indicates that for an assessment of the aerosol extinction in coastal regions the lateral variability must be taken into account.

Trek 5 of H.Nl.Ms. Tydeman was not exactly down wind (course 90°, wind direction around 60°), but there still remained a reasonable longitudinal component and delays in weather changes at MPN and at the ship were expected. With a trek of 75 nMi and a wind speed of 7 m/s, the maximum delay time was in the order of 6 hours. The delay was most clearly observed for the relative humidity (Figure 4), which decreased from 85-90% at the beginning of the trek to a minimum of about 70-75%, and then again increased. The minimum was reached at MPN about 3 hours earlier than at the ship, which corroborated with the ship's position at that time, i.e., midway between the end points. Because the ship sailed towards MPN (facing the wind), the humidity increase at the ship was sharper than at MPN. When the ship reached MPN, similar humidities were measured at both platforms.

A delay was also observed for a change in the aerosol concentration. Figure 5 shows the concentration of 0.5 μm aerosols, corrected to an ambient humidity of 80%. Towards the end of the case (date 301.25, indicated by the arrow in Figure 5), the concentration at MPN increased abruptly. One hour later, the same increase was observed at the ship, which at that time was some 10 nMi from MPN. With the wind speed and wind direction mentioned above, we calculate a transit time of about 1 hour for an air mass from platform to ship. Figure 5 also shows that the amount of 0.5 μm particles measured at ship and platform was essentially the same, i.e., no fetch effect was visible. The fetch may have played a role in the concentration of 5.0 μm particles, which, during the trek, seemed a little more abundant at the ship than at MPN.

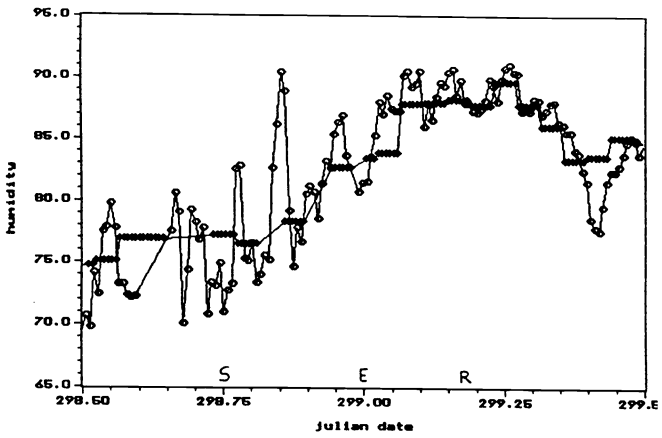

Figure 6: Time series of relative humidity at MPN (✦) and ship (o) during trek 4."S", "E" and "R" denote start, turning point and end of trek, respectively.

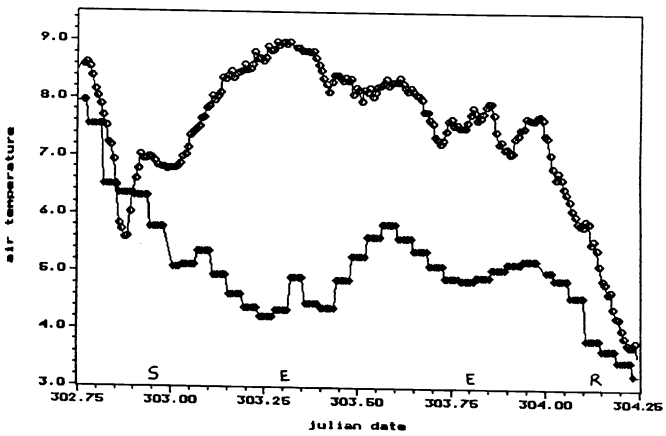

Figure 7: Time series of air temperature at MPN (✦) and ship (o) during trek 7."S", "E" and "R" denote start, anchor period and end of trek, respectively.

During trek 4 the course of H.Nl.Ms. Tydeman was perpendicular to the wind direction (course 300°, wind direction 30°) to a distance of approximately 125 km. This implies that on a synoptic scale the air masses advected by the wind arrived simultaneously at MPN and at the ship, and that changes in meteorological conditions occurred at the same time. Figure 6 presents the time evolution of the relative humidity, which increased from 75% to 90% during the trek. The Figure shows clearly that the time evolution of humidity was similar at the platform and at the ship. The humidity increase was the most prominent feature during the case, but smaller variations in wind speed (5-8 m/s) also ocurred simultaneously at the two stations.

The air mass arriving at the platform had travelled a smaller distance over water than the one arriving at H.Nl.Ms. Tydeman. This fetch difference could show up in the aerosol concentration at both stations. However, ship and platform measured identical concentrations of 0.5 μm aerosols during the trek, and variations were again observed at the same time. Contrary to this, the concentration of larger (5.0 μm) particles measured at the ship on the return leg was somewhat (0.5 log units, i.e., a factor of 2) larger than the concentration measured at MPN, which can be ascribed to the longer fetch.

As mentioned previously, the other treks of H.Nl.Ms. Tydeman cannot be used to study the spatial variability of the aerosol concentration by lack of data. However, these treks are useful to assess the variability in meteorological parameters, in particular the temperature. The MAPTIP experiment was characterised by unstable conditions, i.e., cold air over warm water, with air-sea temperature differences of up to -10°C. Thus, the longer the cold air was advected over the warm water, the more it warmed up and a higher air temperature was expected as the ship was farther away from the coast. In fact, even without advection a higher temperature was expected, because an increase of about 2°C in sea temperature was observed whenever the ship moved away from MPN.

Figure 7 shows the air temperature during trek 7 when H.Nl.Ms. Tydeman sailed down wind to about 200 km of MPN (wind direction approximately 100°). Both stations measured identical temperatures before and after the trek. As soon as the ship sailed from MPN, the air temperature measured at the ship started to rise to a maximum difference of about 3°C, well above the significant difference of 0.2°C (see previous section). The warming of the air parcel with fetch was also observed on other treks, albeit that the difference was not always as pronounced as in Figure 7.

5. CONCLUSIONS

An attempt was made to study the lateral variations of meteorological and aerosol parameters measured at MPN and H.Nl.Ms. Tydeman during MAPTIP. Case studies have been presented that show that weather changes at platform and ship occurred simultaneously when the ship sailed across wind, and with a certain time delay when the ship sailed down wind from MPN. The observed delays correlate well with the distance between the two stations and the wind speed.

The lateral variations induced by fetch effects could be demonstrated for air and sea temperatures, which implies that the length of the treks (maximum 200 km) were sufficient to observe changes in the meteorological parameters. The amount of larger aerosol (mainly of marine origin) seemed to increase with fetch, but the evidence was not conclusive. In contrast, the concentration of smaller aerosols did not decrease significantly when the fetch increased from 20 to 200 km. This could be caused by a replacement of land-originated aerosol by marine aerosol. In open ocean conditions, smaller aerosols are also generated from the sea surface,[11] and the chemical composition of an aerosol sample collected at the extreme of the 200 km trek showed both anthropogenic and marine characteristics.[6] On the other hand, it is also possible that the fetch of 200 km was too short to induce significant variations in the concentration of smaller aerosol. The transit time for an air mass was about 6 hours, whereas the residence time of the aerosol is similar or longer.[4]

6. ACKNOWLEDGEMENTS

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